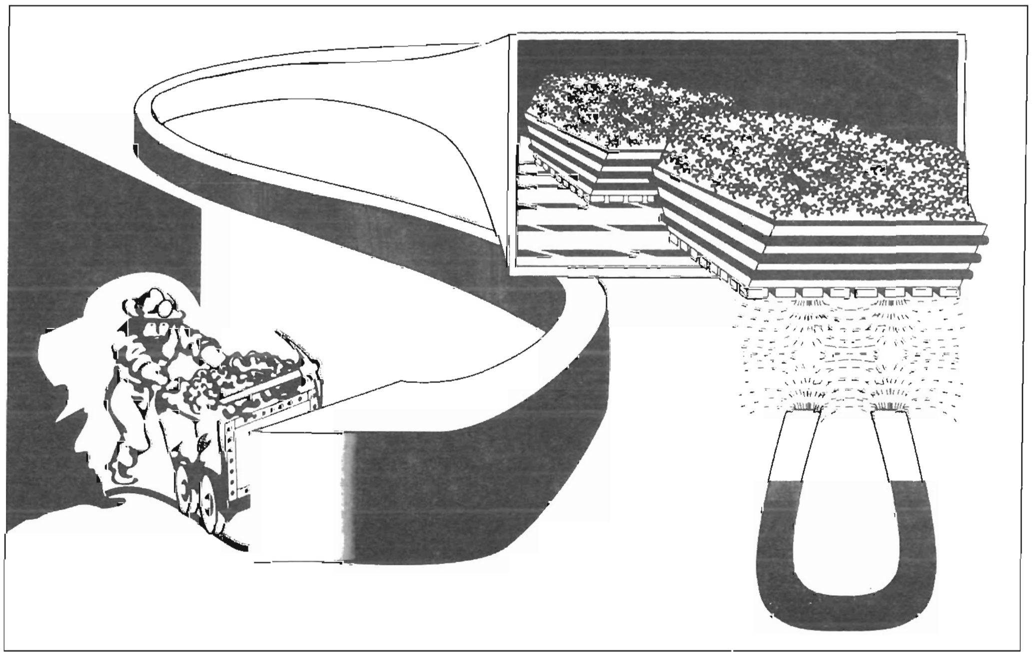
RI 9555

REPORT OF INVESTIGATIONS/1995

Magnetic Levitation Transport of Mining Products



UNITED STATES DEPARTMENT OF THE INTERIOR

UNITED STATES BUREAU OF MINES

U.S. Department of the Interior Mission Statement

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally-owned public lands and natural resources. This includes fostering sound use of our land and water resources; protecting our fish, wildlife, and biological diversity; preserving the environmental and cultural values of our national parks and historical places; and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people by encouraging stewardship and citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.

Cover: Past and future of coal haulage from underground mines. Early techniques included use of push carts; automated magnetic levitation systems may be utilized in the near future.

Report of Investigations 9555

Magnetic Levitation Transport of Mining Products

By J. J. Geraghty, W. E. Wright,
and J. A. Lombardi

UNITED STATES DEPARTMENT OF THE INTERIOR
Bruce Babbitt, Secretary

BUREAU OF MINES
Rhea L. Graham, Director

International Standard Serial Number
ISSN 1066-5552

CONTENTS

ILLUSTRATIONS

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

cm	centimeter	mA	milliampere
kg	kilogram	mm	millimeter
km	kilometer	t/d	metric ton per day
m	meter	V dc	volt, direct current
m/s	meter per second		

MAGNETIC LEVITATION TRANSPORT OF MINING PRODUCTS

By J. J. Geraghty,[1] W. E. Wright,[2] and J. A. Lombardi[3]

ABSTRACT

U.S. Bureau of Mines researchers investigated the development of an innovative transport system for underground coal mining. A one-half commercial-scale bench model was constructed. Novel magnetic levitation (mag-lev) technology was developed. Frictionless and contact-free transport of a prototype materials container and payload has been demonstrated.

[1]Electronics engineer.
[2]Mechanical engineer.
[3]Mining engineer.
Denver Research Center, U.S. Bureau of Mines, Denver, CO.

INTRODUCTION

For many years, the standard materials transport system in underground coal mining has primarily been the conveyor belt. Conveyor belts are the most cost effective of current haulage methods, but they introduce numerous safety hazards. The primary hazard is that of inadvertent worker contact with an operating belt. Conveyor belt systems also may increase the concentration of respirable dust to which mining personnel may be exposed and have been found to cause mine fires from overheated rollers or belt friction points.[4] The costs associated with the resultant injuries and fatalities from belt system safety hazards have an adverse effect on the overall cost of coal production.

The U.S. Bureau of Mines (USBM) recognized the need for a system that would improve the safety and reduce the cost of underground coal haulage. A coal haulage system integration and design study identified pipeline transport systems as the safest, most promising alternative to conveyor belt systems. Coal transport in pipelines was reviewed and analyses were made to determine why past pipeline transport attempts were unsuccessful. From these analyses, the containerized transport of coal in a pipeline was determined to be viable and to meet current coal transport requirements. It was decided that the optimum containerized coal, pipeline transport system design would incorporate magnetically levitated, air-driven containers.

It was determined that magnetic levitation (mag-lev) transport system research would involve radically new haulage system engineering, constituting a high-risk effort. However, the high percentage of mining accidents attributed to underground coal haulage by conveyor belts, coupled with the USBM commitment to improve the safety and reduce the operating costs at mines, prompted the USBM to undertake this research.

SYSTEM DESCRIPTION

A mag-lev transport system design was developed specifically for the transport of coal from an underground coal mine to a surface facility. The system design calls for individual or linked magnetically levitated materials containers to be pneumatically propelled through a concrete pipeline. The bottom of the concrete pipeline would be lined with permanent magnets for container levitation and have steel siderails embedded in the interior to enable container steerage.

The mag-lev transport system development work was performed using a half-commercial-scale prototype model (see figure 1). The model is composed of three components: a transit corridor, a levitated materials container, and a container-mounted electronic position control system. The transit corridor and levitated container each house an array of permanent magnets. The magnet arrays are oriented to repel each other, thereby effecting suspension of the materials container above the transit corridor. The electronic position control system maintains noncontact positioning of the materials container within the transit corridor.

TRANSIT CORRIDOR

The prototype transit corridor, which is approximately 122 cm wide, consists of a wooden base with attached steel siderails. The base houses a chevron-shaped array of oriented ceramic-5 magnets, arranged in 14 alternating polarity columns (see figure 2). The spacing between the columns and rows of magnets is dictated by two factors. First, the spacing must be sufficient to avoid significant field interference between adjacent magnets. Such interference acts to reduce the repelling suspension force of the corridor array.[5] Second, the spacing must be set so that there is a nearly continuous area of magnet interface between the corridor and the materials container during transit. This second factor is interdependent with the spacing of the magnet array in the levitated materials container.

A steel siderail is mounted on both sides of the corridor, extending the entire corridor length. The siderails, which are 15.24 cm tall by 1.27 cm thick, are a necessary element for the operation of the electronic position control system. The system utilizes proximity sensors and electromagnets to determine and maintain a centered position of the levitated container within the transit corridor. The sensors and electromagnets require the presence of a soft magnetic material, such as steel, on both sides of the transit corridor.

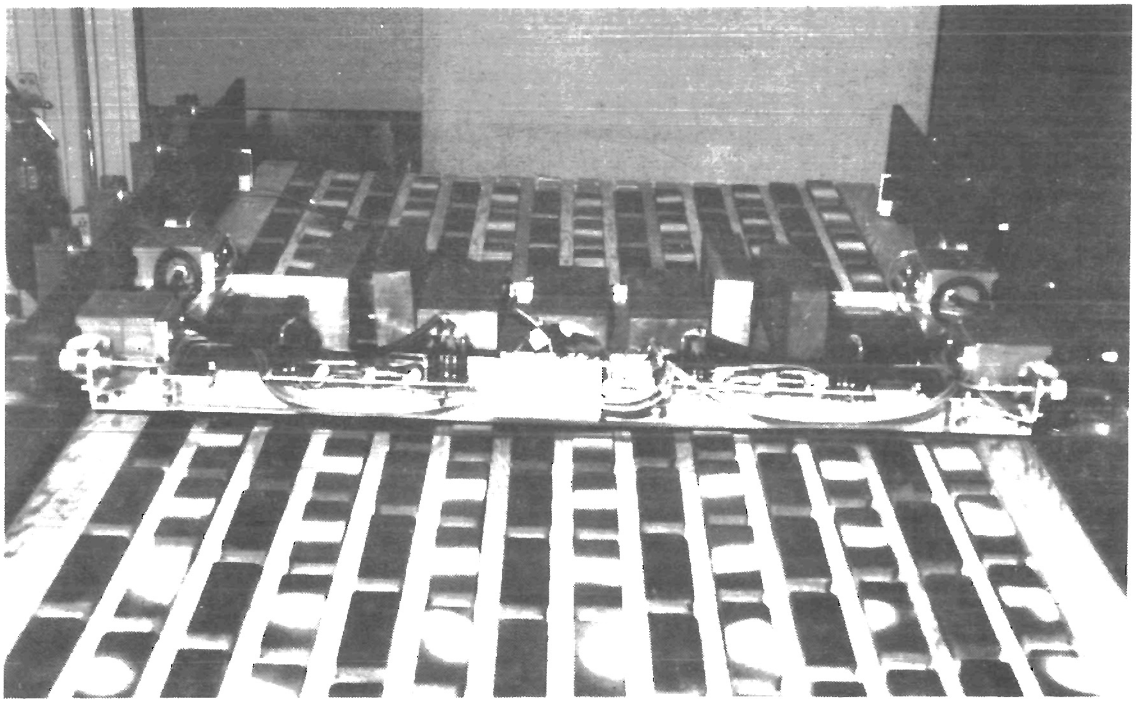
MATERIALS CONTAINER

The prototype materials container consists of a nonmagnetic, rectangular body that houses a rectangular array

[4]Poland, A. P., and J. A. Lombardi. Coal Transport Using Permanent Magnet Levitation. Paper in Proceedings of the International Symposium on Mine Mechanization and Automation (Golden, CO, June 10-13, 1991). CO Sch. Mines, v. 2, 1991, pp. 11-13 to 11-24.

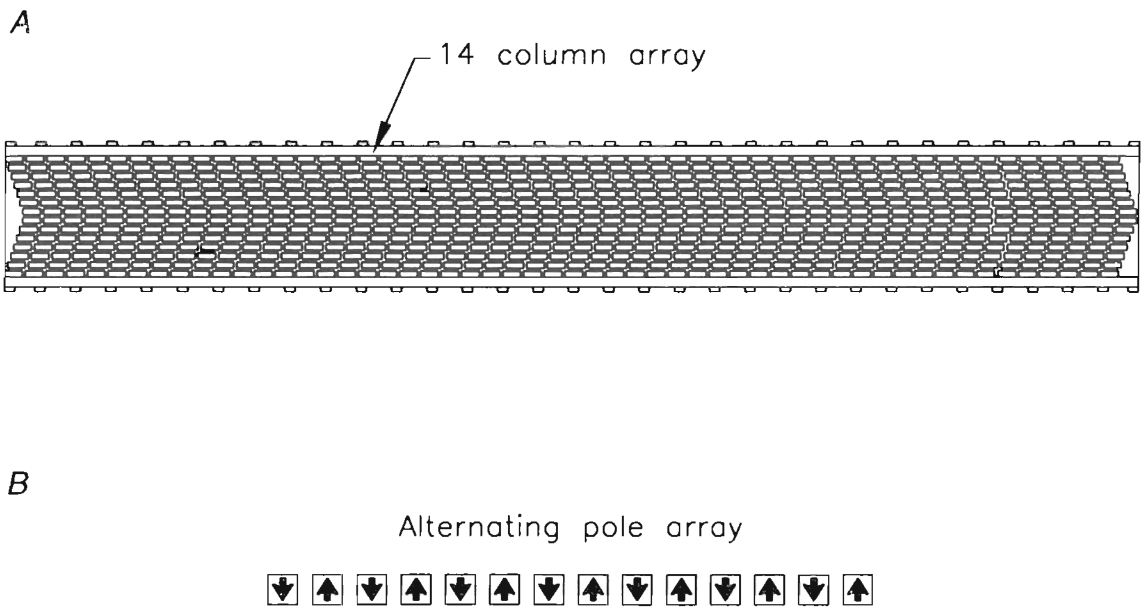
[5]Work cited in footnote 4.

Figure 1



Prototype mag-lev transport system. Materials container, loaded with approximately 85 kg, is magnetically suspended 4 cm above transit corridor.

Figure 2



Transit corridor magnet array. A, Top view; B, end view. (Arrows represent magnet poles.)

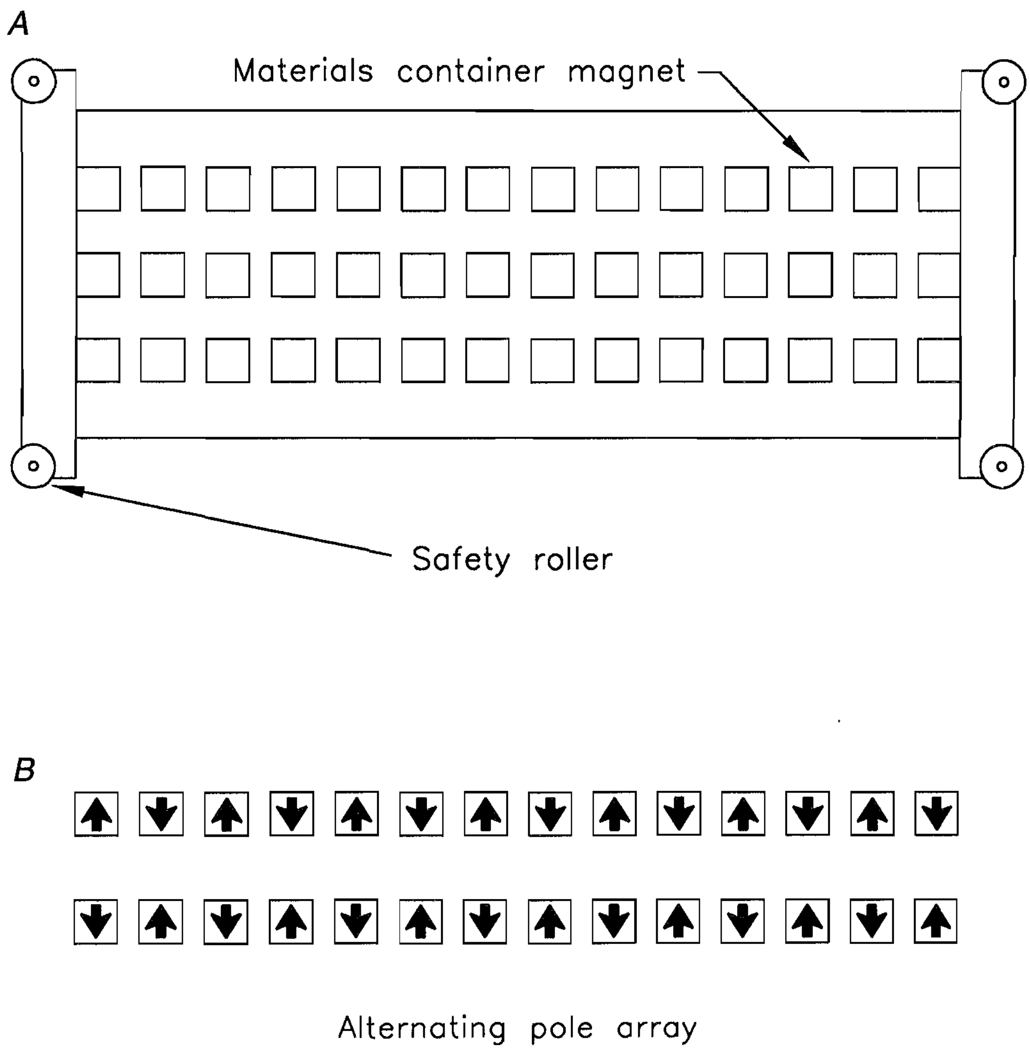
of oriented neodymium-iron-boron magnets. The prototype container, which is approximately 119 cm wide, 60 cm long, and 5 cm tall, represents the base of an actual materials container unit, without the sidewalls. The weight of the prototype materials container, including the magnets and onboard electronic position control system, is approximately 58 kg. The container magnet array is arranged in alternating polarity columns, opposite to the corridor magnet polarities, such that the interface is strictly repulsive (see figure 3). The container magnet array spacing is governed by the same two factors as the transit corridor array—field interference and continuity of magnet interface area.

ELECTRONIC POSITION CONTROL SYSTEM

The repulsive magnetic field suspending the materials container above the transit corridor acts, in accordance with Earnshaw's theorem,[6] to force the container toward either corridor siderail. Earnshaw's theorem states that an object cannot be suspended in stable equilibrium by purely magnetic forces. To overcome this lateral instability, an electronic position control system was installed on the levitated container (see figures 4 and 5). The control system

[6]McCaig, M. Permanent Magnets in Theory and Practice. Halsted Press, 1977, 374 pp.

Figure 3

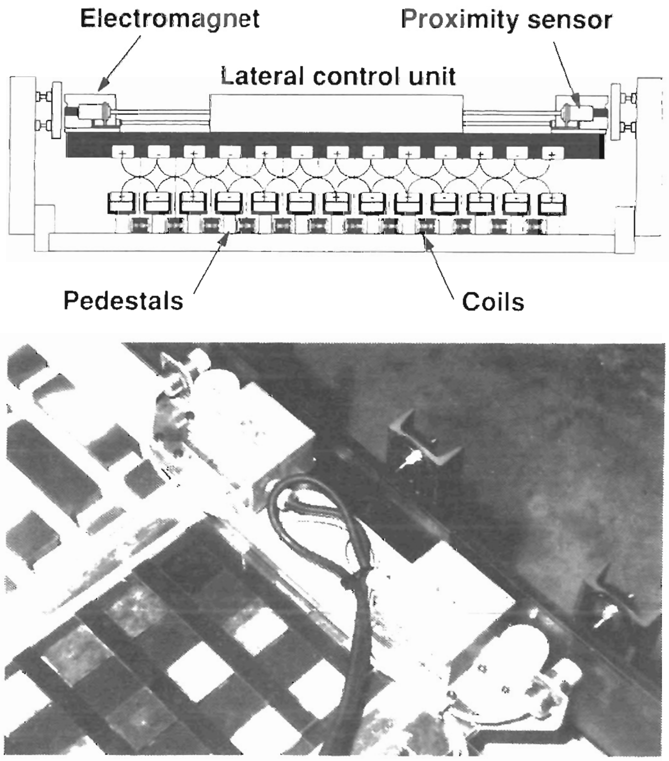


Materials container magnet array (A) and interface of magnets in materials container and transit corridor (B). (Arrows represent magnet poles.)

uses four proximity sensors, one fore and aft on the two container sides facing the siderails, to gather information on the position of the container relative to the siderails. The proximity sensor outputs are processed by a proprietary lateral control circuit. Circuit outputs control four electromagnetic actuators, one located next to each proximity sensor. When the electromagnets are energized, an attraction occurs between them and the steel siderails. By controlling this attraction, the materials container is kept centered between the corridor siderails.

The electronic position control system requires a dc power source for operation. An onboard power generation system has been conceived, but not yet developed. Electrical conductors, perhaps coils, attached to the underside of the levitated materials container, could possibly be used to provide some or all of the power required by the electronic position control system. During container transit, the hanging conductors would intersect the magnetic field present between and/or above the columns of corridor magnets. The current induced in the coils by the coil-field interaction is converted to the necessary voltages

Figure 4



Electronic position control system. Top, System installed on materials container; bottom, proximity sensors and electromagnets on one side of materials container.

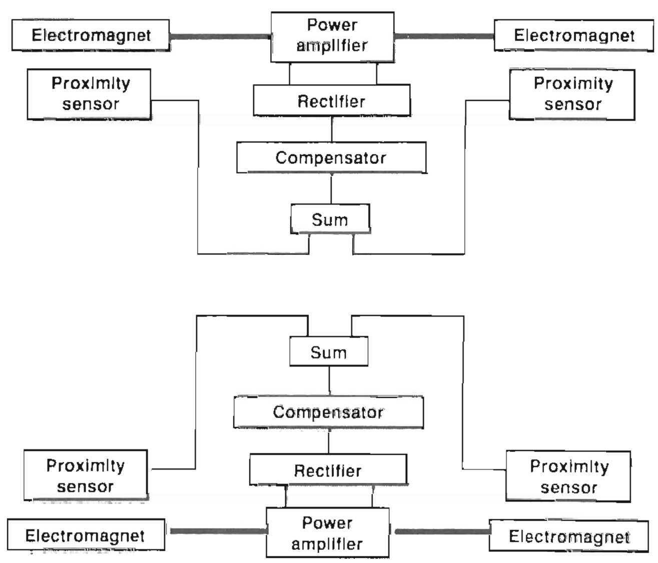
and then distributed to the sensors, electromagnets, and lateral control circuit. Data were collected to provide a geometric profile of the magnetic field intensities. By incorporating this magnetic field profile into a computer model, the optimum power generation coil configuration can be determined.

Lateral Control

A major milestone in the research efforts was the development of an electronic positioning system to overcome the inherent lateral instability of the levitated materials container. The magnetically suspended container exerts lateral forces on the transit corridor siderails because of the orientation of the repulsive magnetic fields. An electronic position control system was developed to provide centered, contactless levitation of the materials container within the transit corridor.

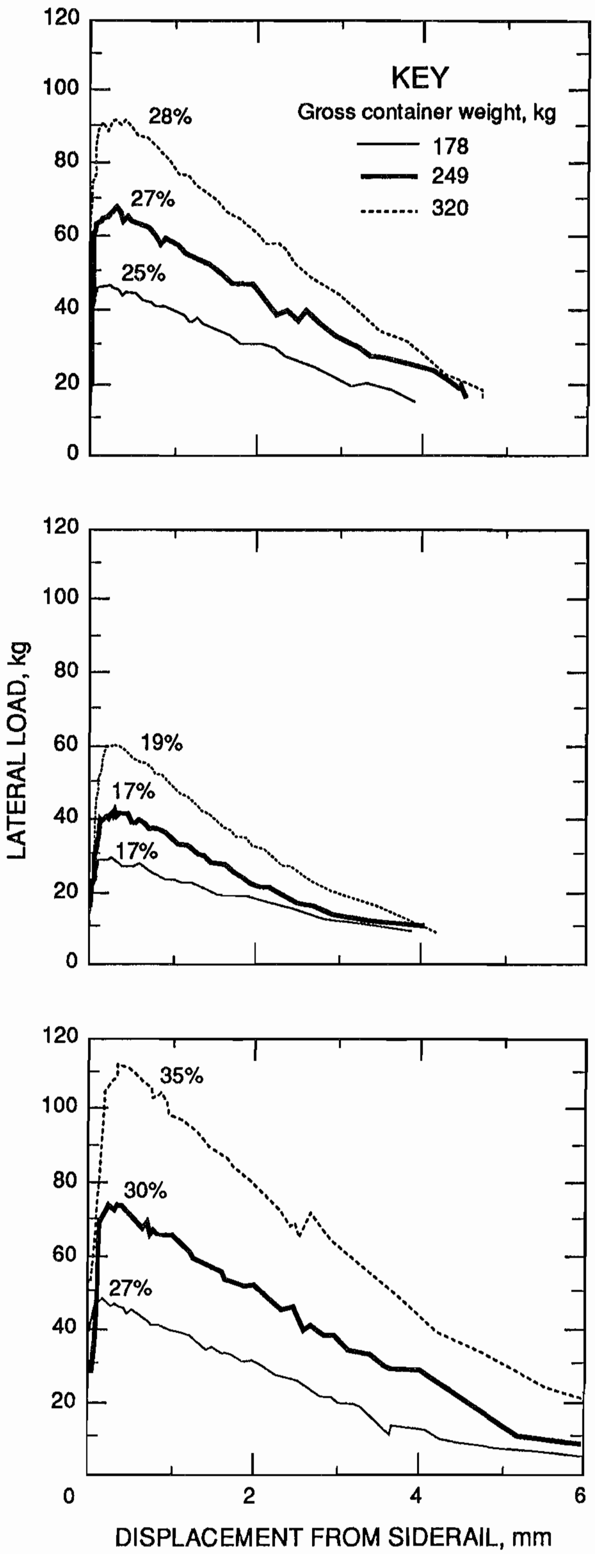
A study was conducted to quantify the lateral force of the suspended materials container toward the corridor siderails. The study provided a profile of the change in lateral load relative to the container displacement from the siderails. Figure 6 presents lateral load measurements at three arbitrarily chosen points along the transit corridor. Lateral load was measured for three different container payloads at each measurement location. As shown in the figure, the lateral load was 17% to 35% of the combined container and payload weights. The data were used to

Figure 5



Block diagram of electronic position control system. Top portion controls front of container; bottom controls rear.

Figure 6



Lateral load versus materials container displacement from siderails at three arbitrary measurement locations. Percentages are the portion of the gross container weight that is transferred laterally.

estimate the forces necessary to manage the lateral instability of the levitated materials container for varying load weights and lateral gaps (container to siderail).

Technical Description

The electronic position control system was developed specifically for the prototype mag-lev transport system. Electronic control systems can be constructed using analog or digital components, or a combination of the two. The analog control system format was deemed most appropriate for the development of a prototype electronic control system largely because of the difficulties associated with synchronizing delay times in digital system design.

In developing the electronic position control system, a computer model of the prototype transport system and proposed position control system was constructed. Transport system physical parameters, control system implementation methods, and component data were incorporated in the computer model. The computer model was used for analysis and simulation studies to evaluate the performance of the proposed position control system on the prototype transport system. The results of the analysis and simulation studies were used to assist in the selection of control structures and parameter values to provide stable operation.

The electronic position control system uses four analog, inductive, proximity sensors, with two installed on both sides of the container that face the steel corridor siderails (see figure 4). Each sensor provides a linear 0 to 20 mA output signal directly proportional to the distance between the sensor face and a metal target, the siderail. The proximity sensors are interfaced to the lateral control circuit such that the outputs of the two front sensors are continuously compared to each other. The two rear sensors are interfaced to the lateral control circuit in the same manner. When the levitated materials container is centered between the corridor siderails, all four proximity sensors produce the same level of output current. When the levitated container is off center, sensor output current levels differ. Comparing proximity sensor output current levels provides a position error signal that directly represents the magnitude and direction of container position error.

The position error data are used to energize electromagnets on the levitated materials container in proportion to the difference between container position and transit corridor centerline. The greater the position error, the greater the level at which the appropriate electromagnets are energized. The strength of the attraction between the electromagnets and the corridor steel siderails varies in accordance with the level at which the electromagnets are energized. By continuously energizing the appropriate electromagnets in response to materials container position error, the levitated container is kept centered between the corridor siderails.

The electronic position control system uses four electromagnets, one located next to each proximity sensor. The electromagnets are 12-V dc bipolar models, each rated at 499 kg holding power.

The proximity sensors and electromagnets are the inputs and outputs, respectively, of the lateral control circuit. The lateral control circuit conditions the sensor outputs, performs first-order, lead-lag dynamic phase compensation, and distributes dc power to the electromagnets. The dc power is supplied by a regulated dc power supply connected to the lateral control circuit.

System Performance

The electronic position control system was installed on the magnetically suspended materials container to evaluate its performance. The position control system demonstrated centered, noncontact positioning of an empty, levitated container traversing a 2.4-m test section of the transit corridor (at approximately 0.25 m/s). The electronic position control system maintained a uniform gap of approximately 3 mm between the corridor siderails and the materials container while traversing the corridor, thus providing totally noncontact, frictionless movement of the levitated container.

The electronic position control system performance was evaluated with load added to the levitated materials container. Noncontact levitation of the materials container was demonstrated while traversing 2.4 m of the transit corridor with a payload of approximately 153 kg in the container (211 kg gross container weight).

PRELIMINARY COST ESTIMATE OF SYSTEM

A preliminary cost estimate was prepared for the proposed mag-lev transport system design. The cost-estimated scenario assumed the transport of 18,000 t/d of coal up a 5% grade over a distance of 4 km. Capital costs for the proposed transport system were developed using both data gained through construction of the prototype and projected data for the system components that had not been demonstrated. The permanent magnet costs data used in the estimate were based on an economy of scale price reduction of 50% less than retail. The preliminary cost estimate indicates the proposed system to be economically viable.

RECOMMENDATIONS

Further research is necessary to complete the development and testing of a mag-lev pipeline transport system. The remaining research can be divided into two main categories: operation and optimization.

The remaining operational research must be performed to allow completion of the prototype construction and system testing. Research in this category includes lateral control of a fully loaded (320 kg gross weight) materials container; analysis of the dynamic behavior of multiple, mechanically linked, loaded materials container trains encountering curves and changes of grade and traveling in the pipeline at the intended operating speed; onboard power generation system studies; and propulsion system studies.

Much of the mag-lev transport system design appears to allow for optimization that would reduce the complexity, cost, and quantity of materials in the original system design. Optimization research should include analysis of an electronic position control system operating off only one siderail instead of both; transposition of the permanent magnet array shapes; lamination of the steel siderails; and use of a hybrid, pneumatic and linear motor propulsion system. Computer simulation studies have indicated that the positioning of the materials containers can be accomplished by sensing only one siderail. Analysis of the system performance in an environment containing curves and change of grade has indicated that the performance can be improved if the chevron-shaped permanent magnet array is located in the materials container and the orthogonal array in the transit corridor. The efficiency of the positioning and propulsion subsystems may be improved by using laminated steel siderails. As the materials containers travel through the pipeline, eddy currents induced in the siderails lead to a loss of attractive force and the development of a drag force.[7] By laminating the siderails, the induced eddy currents should be minimized.

[7]Rodger, D., N. Allen, P. C. Coles, S. Street, P. J. Leonard, and J. F. Eastham. Finite Element Calculation of Forces on a DC Magnet Moving Over an Iron Rail. IEEE Trans. Mag., v. 30, 1994, pp. 4680-4682.

Finally, the propulsion system efficiency may be improved by utilizing a linear motor for acceleration of the loaded materials containers, linked to a pneumatic pipeline to maintain the velocity of the containers. Recent advancements in the area of linear motors and the large air volume requirements for acceleration by pneumatic pressure warrant further investigation of such a hybrid propulsion system.

SUMMARY

The USBM has developed mag-lev technology utilizing permanent magnet suspension coupled with an electronic position control system. Research indicates that this enabling technology may be suitable for development of a mag-lev pipeline transport system. This innovative materials transport system design appears as a promising means to improve the safety and to reduce the cost of underground mining and materials handling. Underground coal transport via a mag-lev pipeline transport system offers many safety benefits over conveyor belt transport, including (1) a reduction in fire hazards due to the elimination of mechanical friction in rotating idler bearings and the use of a nonflammable system enclosure (concrete pipeline) and (2) improved worker health and safety through reduced exposure to respirable dust and moving parts (rotating belt and belt-idler assemblies).

INT.BU.OF MINES,PGH.,PA 30112
☆ U.S.G.P.O. 1995-609-012/ 20,011